THE REACTOR TRAINER: State-of-the-Art ClassRoom Learning

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Abstract - The Reactor Trainer is a professional, PC based, graphically enhanced, training resource specifically developed and customized for Class Room teaching of, and learning about, reactor behavior. This unique, and focused, learning-target sets The Trainer apart from the panorama of the more common PC plant simulator. Its educational scope extends along a logical learning path, starting with important fundamental behavioral concepts of delayed neutrons, neutron multiplying factors, and reactor rate, moving to simple reactor transients in real time, and culminating with more complex operational evolutions. The Trainer empowers the Instructor with a dynamic Class Room demonstrator and the student with a superior hands-on learning tool. The Trainer's versatility encompasses a wide variety of educational needs, including initial operator training, requalification training, Shift Technical Advisor training, and other advanced or specialized training. In addition, The Reactor Trainer enhances prerequisite preparation of operator candidates for full-scale control room training and, in so doing, PC economics relieves full-scale simulator hours.

The Reactor Trainer is a professional, PC based, graphically enhanced, training resource specifically developed and customized for Class Room teaching of, and learning about, reactor behavior ... both basic behavioral concepts and real time behavior. The Trainer, either as a PWR or BWR model, resides on a 3.5" high-density disk, runs in a WINDOWS environment on an IBM compatible computer (386 or better), requires less than 2 mb of RAM, and displays on an EGA monochrome or color monitor. The Trainer package includes a 100 page program manual with more than 25 step-by-step exercises (with technical explanations of behavior and with illustrated screen display printouts). However, the Trainer's ultimate capability is limited only by the imagination of the user.

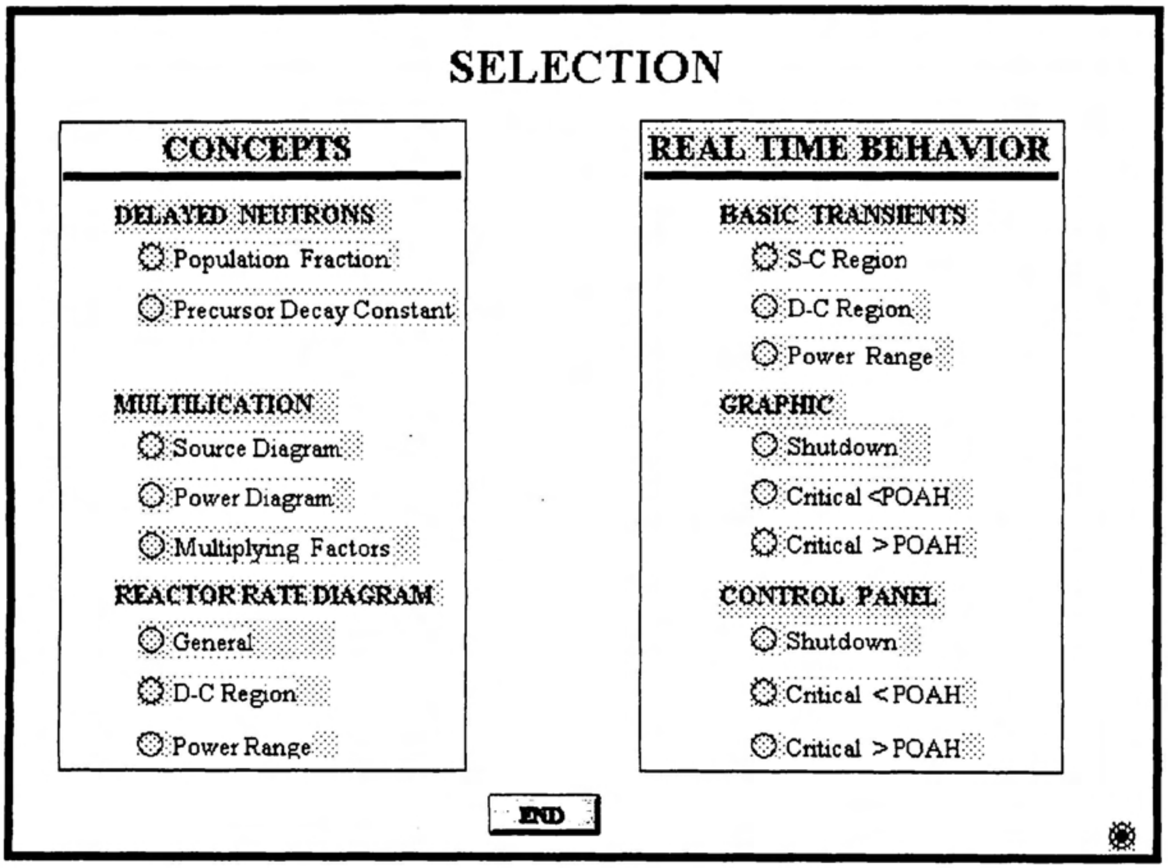
The Trainer employs a point kinetics model with six-delay groups, a non-fission neutron source, control rods with up to three reactivity rates plus scram capability, boron poison control (PWR), a moderator temperature coefficient that may be negative, zero, or positive, a doppler coefficient that may be zero or negative, a void coefficient (BWR), and thermal characteristics associated with reactor power production and steam generation. The program operates in real, or accelerated, time. The range of operation extends from shutdown to full power. The neutronics, a set of coupled neutron and precursor balance equations, are treated by standard numerical methods and have been extensively checked by hand calculation and against published data. A lesser detailed thermal model incorporates time constants and heat capacities tailored to provide responses representative of typical U.S. PWR or BWR commercial plants.

All controls for Trainer exercises are displayed on-screen and are activated by mouse click or press and hold. Three controls are available, namely rod control, steam control, and boron-10 control. Parameter selections and other options are also located on-screen. Special features available with the Trainer include:

- random number generation to set an unknown critical rod position for reactor startup

- o time acceleration to expedite ClassRoom demonstration of extended evolutions
- o simultaneous graphic/meter display to transition from graphic traces to meter response
- o optional digital display of supplementary parameters
- o printout of screen display

Six modules make up the PWR Trainer, illustrated herein, three pertaining to basic concepts and three pertaining to real time behavior. All modules have three subroutines, except for the delayed neutron module, which has two. In all concept graphics, parameters are displayed against reactivity. The three subroutines of each real time module alter the initial conditions for a transient. The seventeen selections are presented on screen by the Module Selection menu, as follows:



The selection desired is activated by clicking on the appropriate option button. In the pages that follow, a brief technical explanation of the purpose of each module is given and an exercise on one subroutine in the module is illustrated and explained.

CONCEPT MODULE 1 - DELAYED NEUTRONS

Module-1 generates two graphics vital to understanding the influence of delayed neutrons and their precursors on reactor behavior, for transient and steady state conditions in both the Delayed-Critical and Sub-Critical regions of operation. These are the POPULATION FRACTION DIAGRAM and the PRECURSOR DECAY CONSTANT DIAGRAM.

Traditionally, neutrons in reactors are categorized by the reaction that produces them. Thus, all neutrons from neutron induced fission are called "fission" neutrons, either prompt fission neutrons or delayed fission neutrons. Neutrons produced by reactions other than neutron induced fission are called "non-fission" neutrons. Typical reactions in this category are (α,n) reactions and spontaneous fission.

A second method of categorizing neutrons, which is perhaps more relevant, is by the function served in the reactor. Non-fission neutrons are always classed as "source" neutrons, because the non-fission reactions produce a source of neutrons for initiating chain reactions. But the function of the fission neutrons is rarely defined. It so happens that the general equation for reactor power, as derived from the neutron balance equation with a single effective precursor group, identifies the function of the fission neutrons, both delayed and prompt. Surprisingly, the prompt and delayed neutrons do not serve the same function. Power is expressed as:

$$P = \frac{\bar{S} + \lambda \cdot \bar{C}}{\beta - \rho} \qquad 1$$

where:

P = power in watts
S-bar = $S/(\nu \times 3.1 \times 10^{10})$
S = non-fission source strength, neutrons/sec
ν = 2.5 neutrons/fission
C-bar = $C/(\nu \times 3.1 \times 10^{10})$
C = core precursor inventory, atoms
λ = the one-group precursor effective decay constant, sec^{-1}
β = precursor yield fraction = 0.0065
ρ = reactivity

Equation 1 is a source multiplication expression which defines reactor power from shutdown to full rated power, for both the steady-state, either as criticality or equilibrium multiplication, and for the transient-state. The numerator on the right-hand-side of this equation indicates that there are two neutron sources in the core, one being the non-fission source, S-bar, and the other being delayed neutrons, $\lambda \cdot$ C-bar. The multiplication of this dual source is always by a factor of $1/(\beta - \rho)$, which accounts for the production of prompt fission neutrons in the ongoing chain reactions. The delayed neutrons initiate chain reactions, just as the non-fission neutrons, and the prompt neutrons propagate the chains.

In Equation 1 the delayed neutrons are represented by a single "effective" delayed neutron group as defined by two important physical properties of the precursor atoms, namely the precursor yield fraction, β, and the precursor effective decay constant, λ_{eff}. However, it is not possible to represent the combined behavior of the conventional six precursor groups by a single precursor having both a constant decay constant, λ, and a constant yield fraction, β. Typically, single group precursor treatment allows the decay constant to vary with the rate of power change (the mix of precursor atoms) while maintaining a constant yield fraction, β.

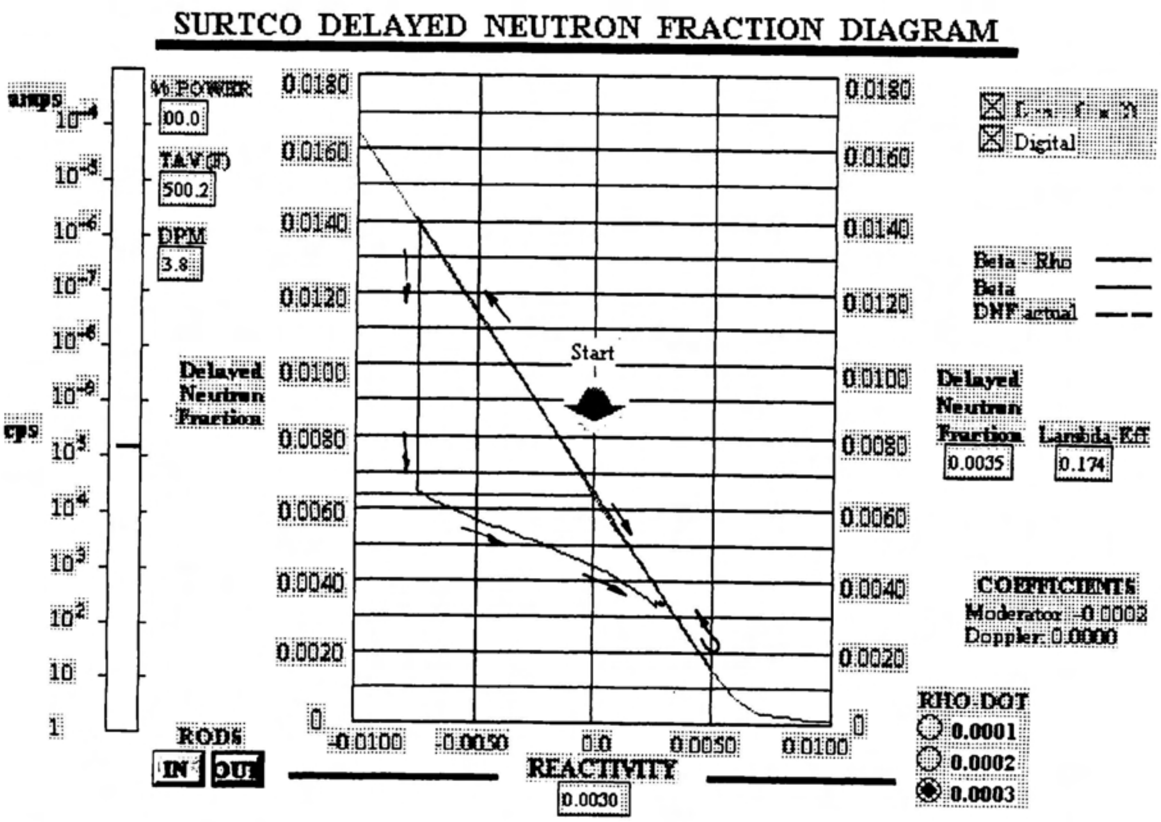
Beta is commonly identified as the "delayed neutron fraction", which is frequently misinterpreted, and misused, as the delayed neutron population fraction. This is not correct, as can be seen by rearranging Equation 1, to give:

$$\beta - \rho = \frac{\bar{S} + \lambda \cdot \bar{C}}{P} \qquad 2$$

Equation 2 states that the total neutron source in the core, non-fission neutrons plus delayed neutrons, is always the fraction $\beta - \rho$ of the total neutron population. For operation in the

Delayed-Critical region, i.e. at power levels high enough to render the non-fission source negligible, leaving delayed neutrons as the sole neutron source, the fraction of neutrons in the total neutron population that are delayed neutrons is always β - ρ. When at steady state, either equilibrium subcritical multiplication or criticality, the fraction of the neutron population that is delayed neutrons is beta. At equilibrium multiplication this results because the non-fission neutrons exactly compensate for the negative reactivity loss of prompt neutrons. At criticality this results because ρ = 0, so that β - ρ reduces to beta. For transitions between the Sub-Critical region, where the non-fission source is significant, and the Delayed-Critical region, the value of the delayed neutron population fraction cannot be defined analytically ... but does display on the Trainer. The importance of the defining the delayed neutron population lies, not in creating a fictitious generation time, but rather because it is the denominator of Equation 2. The inverse of the delayed neutron population fraction defines the extent of neutron source multiplication and reactor power.

The POPULATION FRACTION DIAGRAM generates a track of the delayed neutron population fraction as a function of the reactor nuclear status. The delayed neutron population fraction is the vertical axis and reactivity is the horizontal axis. A downward sloping line, from the upper left to lower right corner of the diagram, represents the fraction β - ρ. A horizontal dashed line extending from ρ= -0.0300 to criticality represents the steady state fraction β. The actual delayed neutron population fraction, calculated by ratioing the delayed to the total neutron population, is tracked as reactivity change occurs. The POPULATION FRACTION DIAGRAM below illustrates the dynamic character of the delayed neutron population fraction, β - ρ.



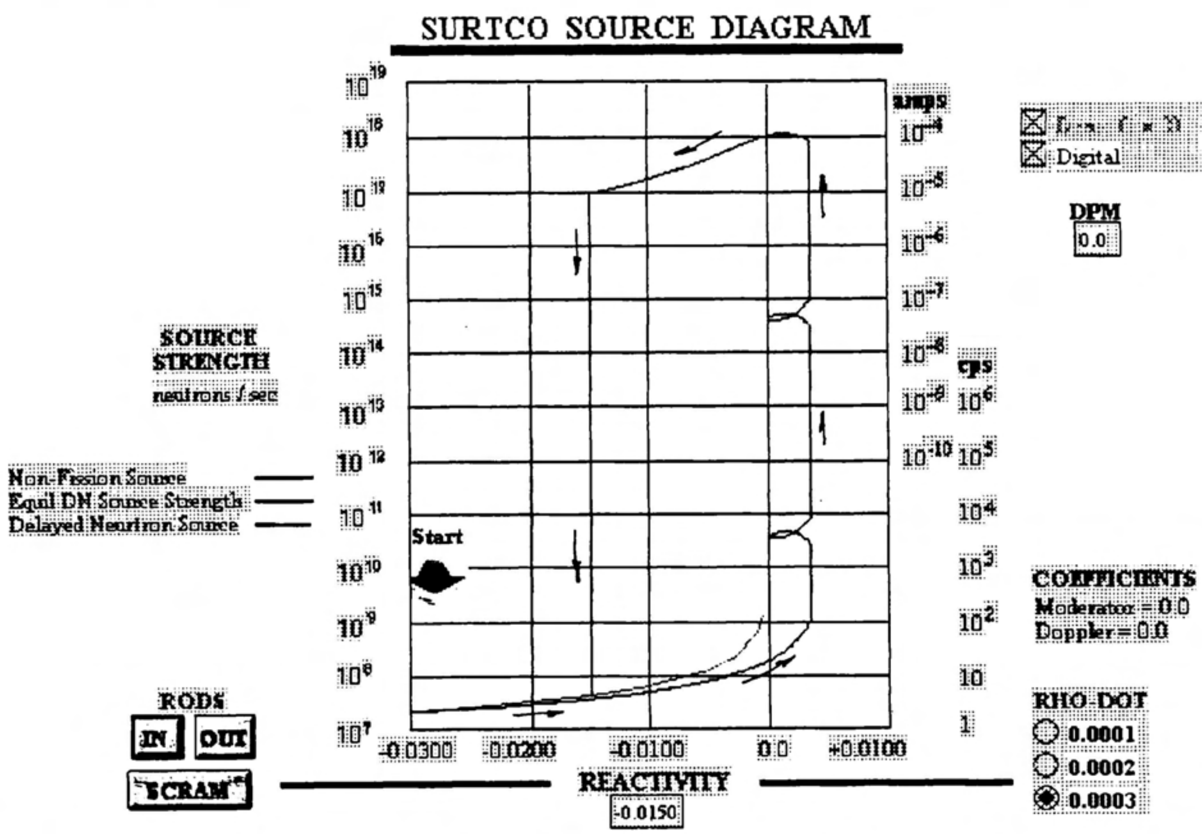
This graphic was generated by an ongoing ramp-out, addition of positive reactivity, from an initial condition of criticality to ρ = +0.0050. The delayed neutron population fraction decreases, tracking along the $\beta - \rho$ line. On reversal to continuous ramp-in to a reactivity of -0.0075, the delayed neutron population fraction increases, again by tracking along the $\beta - \rho$ line. With reactivity constant at -0.0075, power decreases into the lower region of the Source Range, to equilibrium multiplication. As the non-fission source becomes significant, the delayed neutron population fraction gradually decreases from $\beta - \rho$ to β. On ramp-out from equilibrium multiplication, the delayed neutron population fraction moves from the β line to the $\beta - \rho$ line.

The PRECURSOR DECAY CONSTANT DIAGRAM deals with the variability of a single group precursor decay constant, λ-effective. The actual value of λ-effective is calculated by a concentration weighting of decay constants for the six precursor groups, being simply a function of the group mix. Taken together, the two graphics in this Module fully define the relevant precursor/delayed neutron behavior in a nuclear reactor.

CONCEPT MODULE 2 - MULTIPLYING FACTORS

Module-2 generates three graphics which demonstrate how a pair of multiplying factors interact to produce full power. These graphics are the SOURCE DIAGRAM, the MULTIPLYING FACTOR DIAGRAM, and the POWER DIAGRAM.

Only two terms on the right-hand-side of Equation 1 contribute to the increase in power from shutdown to full power. These are the delayed neutron source strength, $\lambda \cdot$ C-bar, and the source multiplication factor, $1/(\beta - \rho)$. The delayed neutron source strength is, by far, the larger and more important of the two.



The SOURCE DIAGRAM generates the delayed neutron source strength, from shutdown to full-power (3000 Mwt), displaying source strength on the vertical axis versus reactivity on the horizontal axis. A horizontal dashed line extending from ρ= -0.0300 to criticality represents the constant strength of the non-fission neutron source, at 1×10^8 neutrons/second. The rising curve extending over the same reactivity range and crossing the non-fission source strength is the delayed neutron source strength at equilibrium subcritical multiplication. Note that the non-fission source strength is significantly greater than the delayed neutron source strength at shutdown. The two source strengths are equal when reactivity is equivalent to minus β, i.e. with ρ = -0.0065. Thereafter, the delayed neutron source is stronger than the non-fission source. The example, on the preceding page, illustrates the dynamic nature, and enormous range, of the delayed neutron source strength.

This graphic was generated by an ongoing ramp-out (positive reactivity addition), from an initial shutdown condition to ρ = +0.0035. During the subcritical portion of the ramp, the actual source strength, λ· C-bar, tracks just below its equilibrium curve. Once supercritical, where precursor production exceeds precursor loss, the source strength increases by several factors-of-ten. It is this increase in delayed neutron source strength that primarily accounts for the supercritical increase in power, to rated power. On ramp-in from its maximum value, the delayed neutron source strength decreases until reactivity insertion is terminated at ρ = -0.0150. Thereafter, source decay continues until reaching its equilibrium strength.

The MULTIPLYING FACTOR DIAGRAM generates normalized source strength, normalized source multiplication factor, and normalized power to illustrate the relative magnitudes of the multiplying factors. The utility of normalization is that any increase in power above shutdown must be due to the product of the increase in source strength and increase in source multiplication factor.

The POWER DIAGRAM provides a track of steady state power from shutdown to full power, which verifies Equation 1 and mirrors the delayed neutron source increase. The subcritical portion of the power curve is known as the equilibrium subcritical multiplication curve. The critical portion of the power curve, actually a vertical line at ρ = 0, is the criticality curve. The continuity of the power curve from shutdown to full power reflects the undergoing physical process as always one of source multiplication.

Taken together, the three graphics in this Module exhibit the underlying factors for all power change. There are no others.

CONCEPT MODULE 3 - THE REACTOR RATE DIAGRAM

Module-3 generates three graphics which relate power behavior, i.e. power change with time, to the nuclear status of the reactor, as expressed in terms of reactivity. This topic is crucial to the reactor operator because control room decisions and judgements require a thorough understanding of this relationship.

"Reactor Rate" is a measure of the rapidity and direction of power change with time. Two properties of the reactor rate are important:

1. The algebraic sign of the rate - determines the direction of power change with time. A positive rate is associated with reactor power increase. A negative rate is associated with reactor power decrease.

2. The magnitude of the rate - determines the rapidity of power change. The larger the value of the rate, the faster the power change with time, whether increasing or decreasing. If the rate is constant at "zero" DPM, then power is at a steady state condition.

For PWRs, Reactor Rate is frequently referred to as the reactor Startup Rate. In equation form it is expressed as:

$$SUR = 26 \times \frac{\dot{\rho} + \lambda \times \rho + \lambda \times \bar{S}/P}{\beta - \rho} \qquad 3$$

where: *SUR = reactor startup rate, decades-per-minute (DPM)*
ρ-dot = reactivity rate, Δρ/sec
λ = one group precursor effective decay constant, sec^{-1}
ρ = reactivity
S-bar = $S/(\nu \times 3.1 \times 10^{10})$*, watts*
S = non-fission neutron source strength, neutrons/sec
ν = 2.5 neutrons/fission
P = power, watts
β = precursor yield fraction

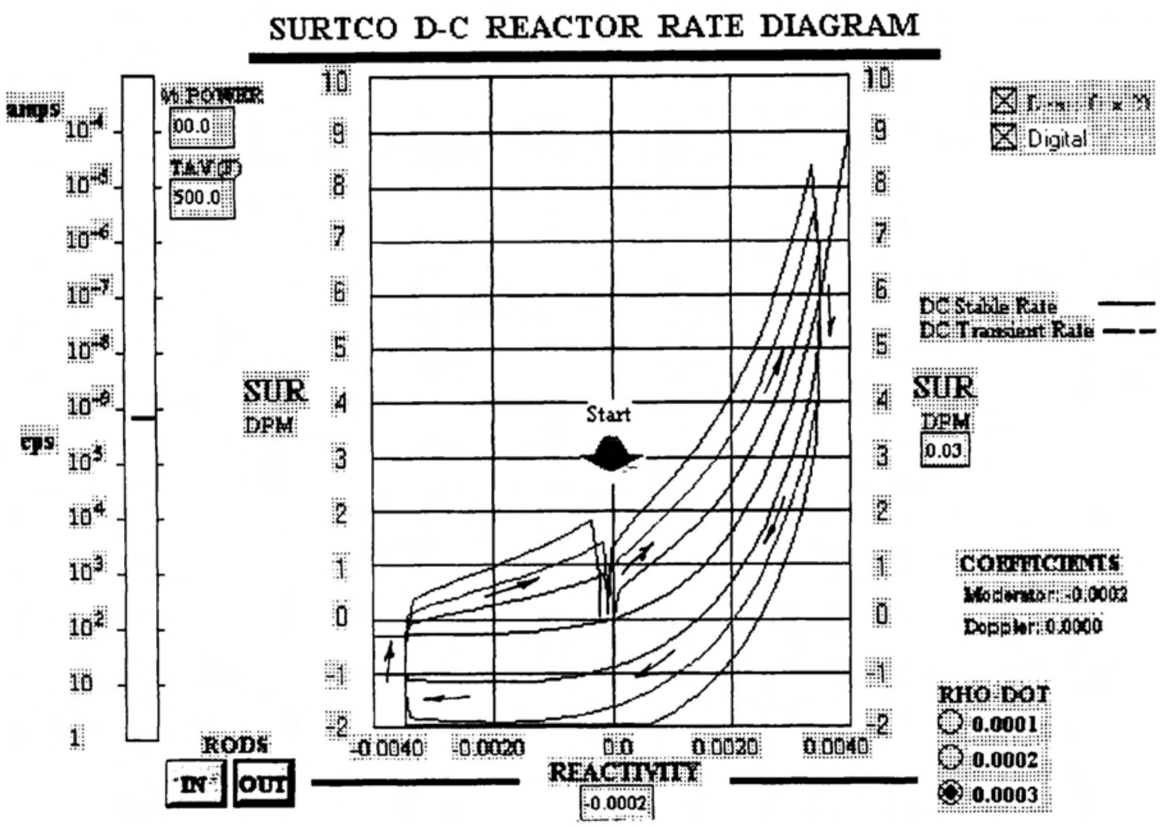
Equation 3 is the general equation for reactor rate and applies from shutdown to full power. Over this range there are two regions of behavior, namely the Sub-Critical Region and the Delayed-Critical Region. In the Sub-Critical Region reactivity is always negative and the non-fission source, being significant, contributes to the overall rate. The reactor rate in the Sub-Critical Region is dependent on three factors, namely ρ, ρ-dot, and S-bar/P. In the Delayed-Critical Region, reactivity may be either positive or negative and the non-fission source term is insignificant. Delayed neutrons act as source neutrons. Even without the non-fission source term, Equation 3 indicates that reactor rate in the Delayed-Critical Region is always dependent on two factors, namely ρ and ρ-dot.

Reactor Startup Rate is the number of base units, i.e. factors-of-10, that power changes in a single time unit (minute). During power change with time, the reactor rate is either a "stable" rate or a "transient" rate. If the reactor rate is constant with time, as associated with exponential power change, the reactor rate is referred to as a "stable" reactor rate. If the reactor rate is not constant but is changing with time, as for non-exponential power change, the reactor rate is referred to as a "transient" rate.

The Reactor Rate Diagrams are graphical displays of the relationship of reactor rate to reactivity, with the vertical axis as reactor rate in decades-per-minute and the horizontal axis as reactivity. Reactivity change is available by ramp-out and ramp-in, with up to three reactivity rates to generate a set of parametric curves. Reactor rate, as calculated from the fractional rate of change in power (ΔP/P)/Δt, is tracked in real time as reactivity change occurs. The three graphics are:

1. The General Reactor Rate Diagram: takes reactor rate from the shutdown condition, through the Sub-Critical Region, into the Delayed-Critical Region, and up to the lower part of the Power Range. This Diagram comes closest to representing an (Integrated) Reactor Rate Diagram that covers all conditions of reactor operation. It is particularly effective for illustrating the rate transition between the two regions.

2. The Delayed-Critical Reactor Rate Diagram: extends from the attainment of criticality, where non-fission neutrons become negligible to the Point-of-Adding-Heat (POAH). In this region reactivity is assumed to be constant unless ramp-out or ramp-in is underway. The displayed stable rate curve is of sharp upward curvature as reactivity moves from negative to positive. The D-C graphic is particularly effective for demonstrating thermal effects at the POAH and for emphasizing that reactivity, alone, does not determine the direction of power change. The example below illustrates the dynamic nature of reactor rate, its dependence on the value of the reactivity rate, and the overall character of reactor behavior around the common operational condition of criticality:



This graphic was generated by initiating an ongoing ramp-out (positive reactivity addition), from an initial shutdown condition of criticality to $\rho = +0.0035$. Note that the reactor rate moves downscale to the stable rate curve on termination of ramp-out. The transient ramp-in curve is then created by continuous ramp-in (negative reactivity addition) to the negative limit of $\rho = -0.0035$. The reactor rate moves upscale to the stable rate curve as the ramp-in terminates. Finally, the loop is completed by ramp-out to criticality. Transient reactor rate curves for two alternate reactivity rates are generated in the same manner. Observe that the transient rate roughly parallels the stable rate curve but that displacement from the stable rate increases with increasing ρ-dot.

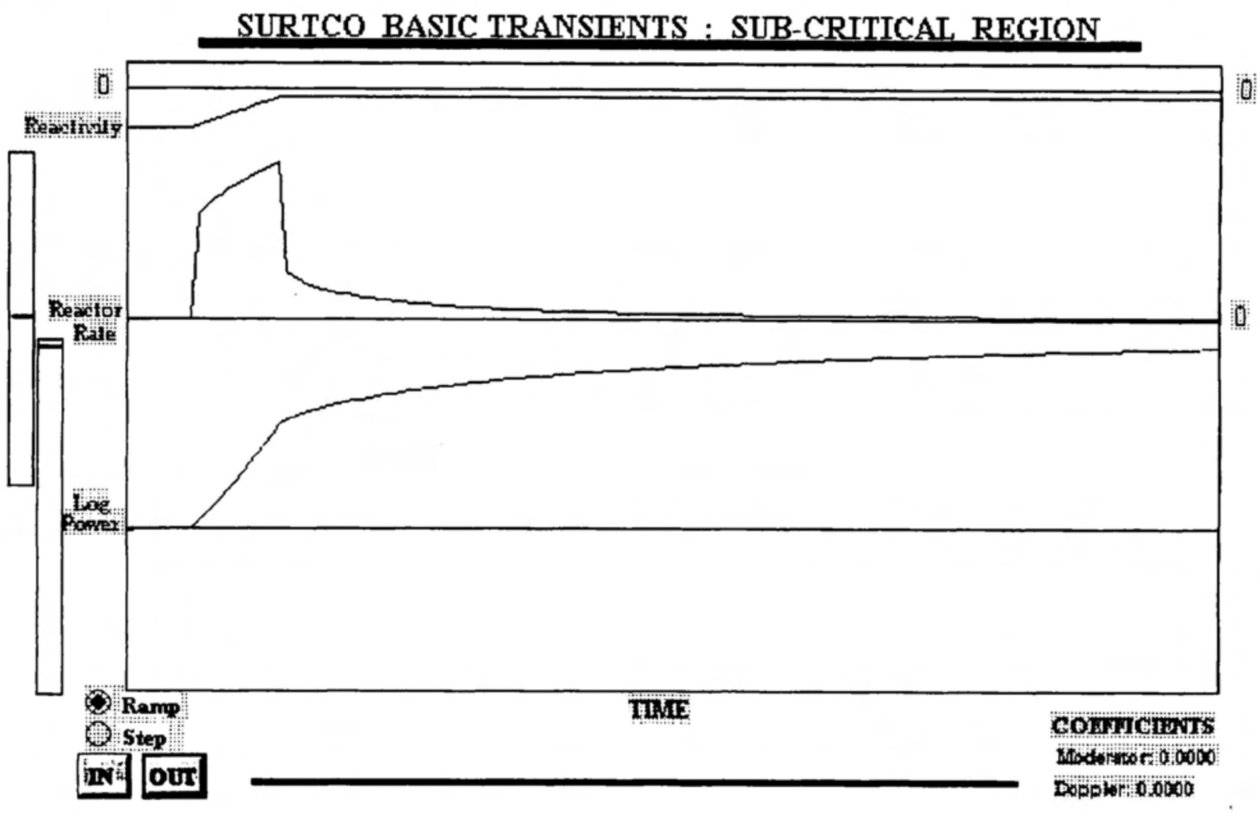
3. The PWR Power-Range Reactor Rate Diagram: applies to the entire Power Range, from 1% (the POAH) to 100% power. In the Power Range, thermal effects due to energy imbalances when off of steady state preclude a stable rate. A stable rate exists only at the steady state condition of criticality, SUR = 0.0 DPM, with reactor power and steam

demand equal. This graphic is particularly effective for demonstrating rate response to rod ramp and steam demand in the power range, and in contrasting rate behavior in the Power Range to that in the D-C Region below the POAH.

REAL TIME MODULE-4: BASIC TRANSIENTS

In moving from concepts to real time behavior it is helpful to build the students understanding of reactor behavior on a solid foundation, by starting with simple transients that are presented in an organized manner, while using a minimal set of parameters. It so happens that reactor transients exhibit certain important identifiable characteristics depending on the type of reactivity change and the Region of power operation. In effect there is a select group of a dozen "basic" transients that should be immediately recognizable by the student, or trainee. To demonstrate these basic transients, two types of reactivity change are used, namely a relatively slow reactivity ramp over a short time interval and a step (instantaneous) change in reactivity. The power response to the two types of reactivity change is notably different in the three Regions of operation, i.e. the S-C Region, the D-C Region (<POAH), and the Power Range.

The example below illustrates the time response of three parameters, namely reactivity, reactor rate, and power, for a short ramp-out in the Sub-Critical region:

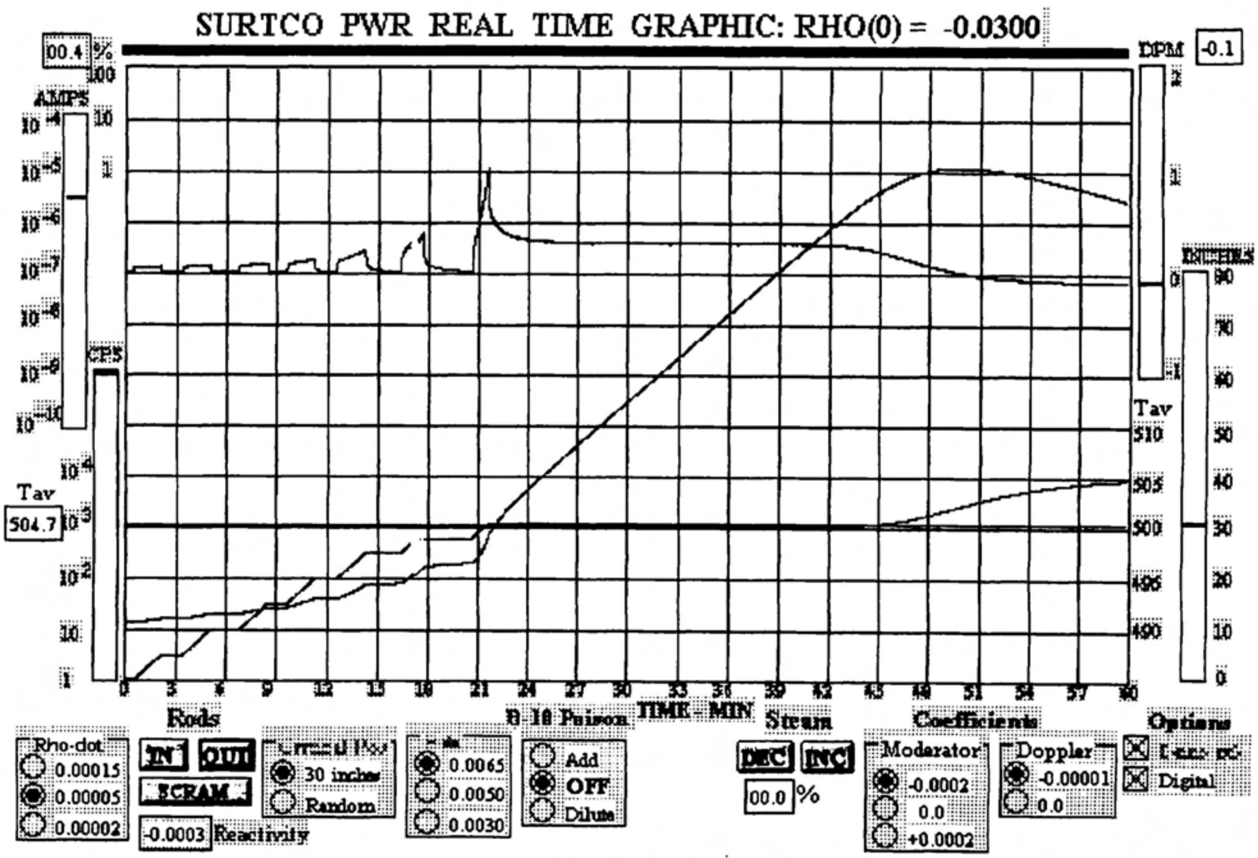


This graphic was generated by initiating ramp-out (positive reactivity addition), from an initial condition of equilibrium subcritical multiplication. The short ramp-out is automatically terminated while still subcritical in order to contain the transient in the Sub-Critical region. At final constant reactivity power continues to increase at a decelerating rate until reaching a higher equilibrium power level. Each of these transients should be discussed in detail with the student to ensure understanding. This type graphic is effective for first defining the shape of reactor rate with time, and for relating that shape to the Reactor Rate Diagram. In addition, the graphic contains primitive meters, which are a first step in weaning the student from the familiar graphic to meter behavior. A thorough understanding of simple transients provides for an easier introduction to operational transients because the more complex transients tend to be a synthesis of the simple transients.

REAL-TIME MODULE 5: GRAPHIC / METER DISPLAY

The PWR Graphic/Meter Display allows for more complex, operational type, transients. The vertical axis of the graphic displays four, or more, reactor parameters. The horizontal axis is time, which extends to a 60 minute limit. The graphic is bounded on the left and right by simple vertical meters. The scales are common for the graphics and the meters so that graphic and meter responses are directly comparable.

The graphic provides the student with a familiar ClassRoom reference. The principle difference is that whereas the ClassRoom reference is a static display of a completed transient, the Trainer graphic evolves in real time as the transient occurs. The meters expose the student to a new, and most likely foreign, form of information presentation, typically lacking in the ClassRoom. There is no track for comparison to the past, or for knowing the future, only the instantaneous indication of the present. This is where the transition from relying on a graphic to relying on a meter should be made.



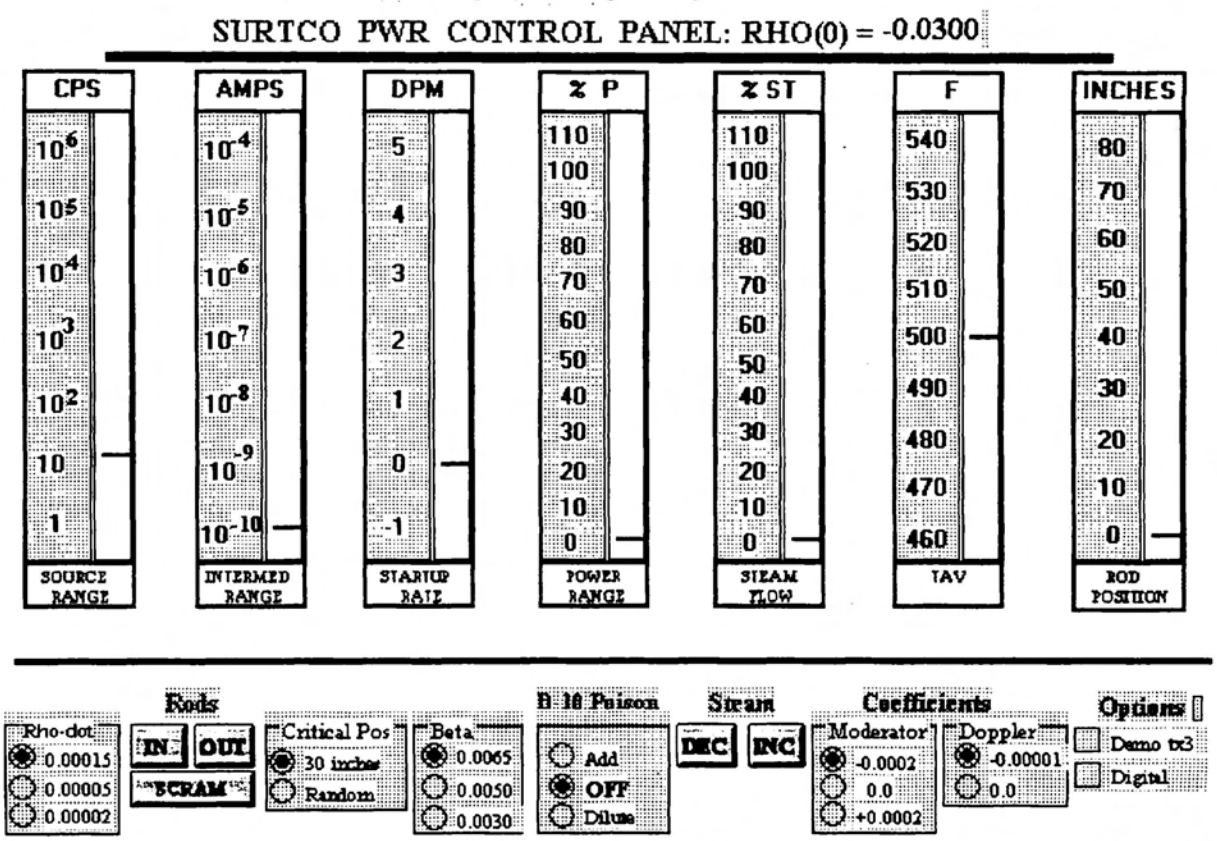
The PWR Graphic/ Meter Display allows for a selection of three distinct initial conditions so as to perform specific major evolutions, as follows:

1. Reactor shutdown
   Reactor startup to POAH
2. Reactor critical in the Intermediate Range
   Heatup of moderator/coolant
   Reactor shutdown - normal or scram
3. Reactor critical in the Power Range (20% rated power)
   Reactor power change by steam demand
   TAV adjustment by control rods and/or Boron

The example, on the preceding page, illustrates the time response of four parameters, namely rod position, reactor rate, power, and Tav, for a simple reactor startup evolution. This graphic was generated by a series of rod withdrawal increments (positive reactivity additions), from an initial condition of shutdown ($\rho = -0.0300$). After the seventh withdrawal increment, a positive stable rate of +0.3 DPM is obtained, indicating that the reactor is critical. Power is allowed to increase through the Source and Intermediate Range, until the point of adding heat (POAH) is reached. Without steam demand, Tav increases until the reactor is subcritical and power then decays to below the POAH. This graphic is particularly effective for explaining and demonstrating the tell-tale change in rate behavior as criticality is approached, the means for identifying criticality, and the method for determining when the POAH is reached. In addition, this module prepares the way for performing operational evolutions on the final module, the PWR CONTROL PANEL.

REAL-TIME MODULE 6 - THE PWR CONTROL PANEL

The PWR - Control Panel provides the same three initial conditions and is used to perform the same transients as the Graphic/Meter Display. The primary differences are that control must be



strictly based on meter display, without any graphic assist for those more comfortable with graphics, and the exercises are not limited by the 60 minute constraint of the graphic time scale.

The Control Panel, as displayed on the preceding page, consists of seven vertical meters. From left to right these are Source Range (cps), Intermediate Range (amps), Startup Rate (DPM), Power Range (%), Steam Flow (%), TAV (°F), and Rod Position (inches).

Summary - The study of reactor behavior is about reactor power change with time. Time is the paramount variable. The Reactor Trainer brings real time into your Class Room lesson.

Several effective techniques exist for employing The Reactor Trainer, including Instructor Class Room demonstration, Instructor workshop, small group demonstration, Instructor supervised Student operation, Student assignment and Class Room explanation, and Student self study. All of these methods offer major advantage over the standard Class Room lecture or textbook study. It is widely recognized that hands-on learning produces extraordinary gains in learning effectiveness, typically by more than a factor-of-two over conventional Class Room show-and-tell. In recent years, both a Carnegie Commission and the prestigious National Academy of Sciences have called for increased use of hands-on learning to raise the instructional level. For some time, many U.S. Nuclear Training Departments have successfully employed special hardware, in the form of equipment, panels, tools, and components, to supplement Class Room Training. As personal computer processing power has grown, the PC becomes an ideal vehicle for boosting the teaching of reactor behavior in the Class Room.

The demonstrated benefit of using The Reactor Trainer is an exceptional gain in learning effectiveness, arising from two extremely positive transformations: (1) it converts the Instructor from a purveyor of facts to a facilitator of learning, and (2) it converts the Students from dormant listeners to active participants in the learning process. Such has been reflected in joint Instructor-Student enthusiasm following experience with The Trainer. In addition, The Reactor Trainer enhances prerequisite preparation for full-scale control room training and, in so doing, PC economics relieves full-scale simulator hours.